OSCAR: Online Services for Correcting Atmosphere in Radar

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Outline

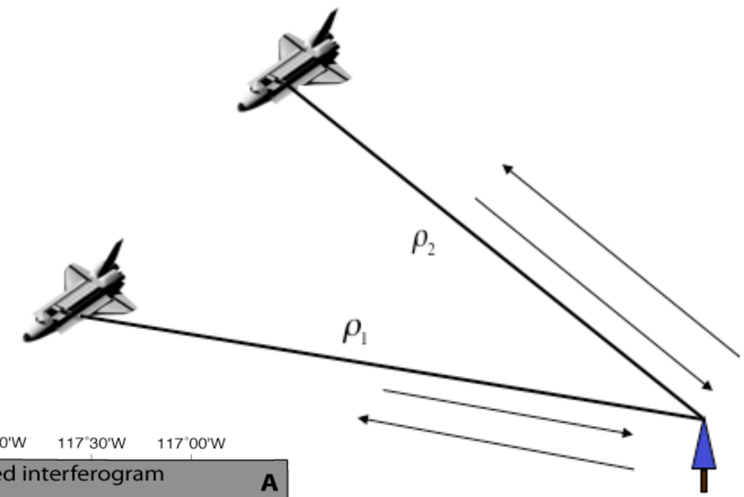
- Objectives and background
- OSCAR IT structure
- Corrections algorithm
- Applications
- Conclusion

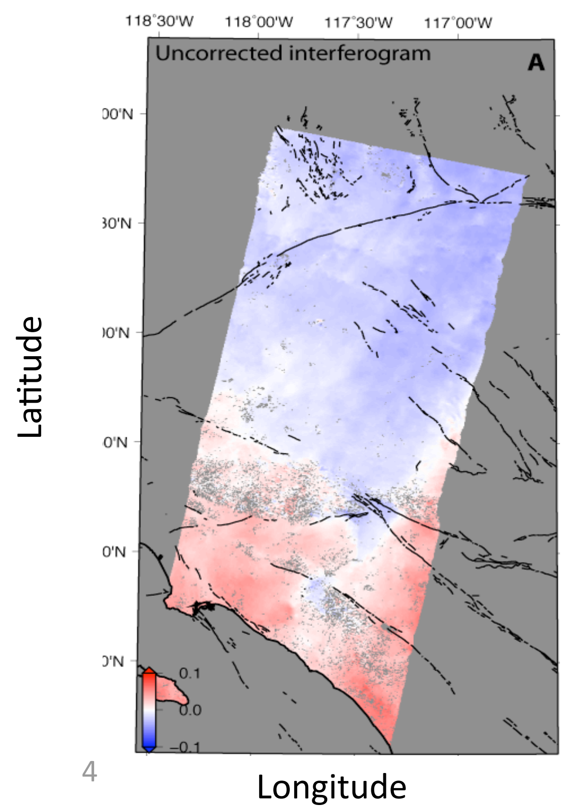
Objectives and background

Why is OSCAR needed?

InSAR Geodetic Imaging

- Interferometric combination of Synthetic Aperture Radar (SAR) images is InSAR
- InSAR measures motion of Earth's surface by phase difference between two SAR images acquired at different times
- Phase of SAR affected by propagation delay in atmosphere
- Variations of propagation delays largest source of error in InSAR measurements





Atmospheric Propagation of Radar

- Radar wavelengths used in InSAR between 3 cm and 60 cm
- Major atmospheric delays at these wavelengths: tropospheric water vapor and ionospheric ion density
- Ionospheric delay is small for C-band (6 cm) SAR archive
  - Delay is strongly wavelength-dependent, and affects longer wavelengths more strongly
- Tropospheric delay is largest variable source of atmospheric delay
- We concentrate on tropospheric water vapor and dry mass for OSCAR, may add ionosphere later

Tropospheric water vapor

- Water vapor delay of radar propagation is non-dispersive (affects all wavelengths equally)
- Large temporal and spatial variability
  - Seasonal and weather-induced.
  - Power-law dependent decreasing power at shorter distances.
- Stratified water vapor vertical gradient change and dry atmospheric pressure changes cause delays correlated with topography

InSAR tropospheric water vapor corrections

- Time series filtering or estimation
- Correlation of phase with topography

InSAR Derived

- CGPS (Continuous Global Positioning System) zenith wet delay interpolated spatially (and temporally)

Ground-Based

- Total column water vapor from absorption of reflected near IR (MODIS and MERIS)
- Water vapor measurements (profiling and total column) from thermal IR and MW (AIRS, MODIS, AMSU)

Remote-Sensed

- European Center for Medium Range Weather Forecasting (ECMWF)
- NOAA NCEP North American Mesoscale Model (NAM)

Numerical Weather Forecast Models

- **OSCAR is web service which locates, retrieves, and merges these data sets to derive an optimal, best estimate of tropospheric delay**

Summary of InSAR Delay Correction Algorithms

General

$$\varphi = \frac{k_0}{\cos\theta}\int_{z_S}^{\infty} \underbrace{k_1\frac{P}{T}}_{\text{Dry}} + \underbrace{W\frac{P}{T}\left(k_2 + \frac{k_3}{T}\right)}_{\text{Wet}} dz$$

The wet and dry atmospheric delays are related to surface pressure (*P*), surface elevation (z_s), viewing angle (θ) and temperature and water vapor profiles (*T,W*).

MODIS

Estimate of delay $$D = Aw$$

At present, constant A=6.2 determined from comparison with GPS zenith total delay (Li *et al*., 2005), w is the MODIS NIR total precipitable water vapor

ECMWF

Estimate of delay $$D = \sum_{i=1}^{N} \frac{2\pi d_i^{SBL}}{\lambda}\left(n_i^{(vapor)} - n_i^{(dry)}\right)$$

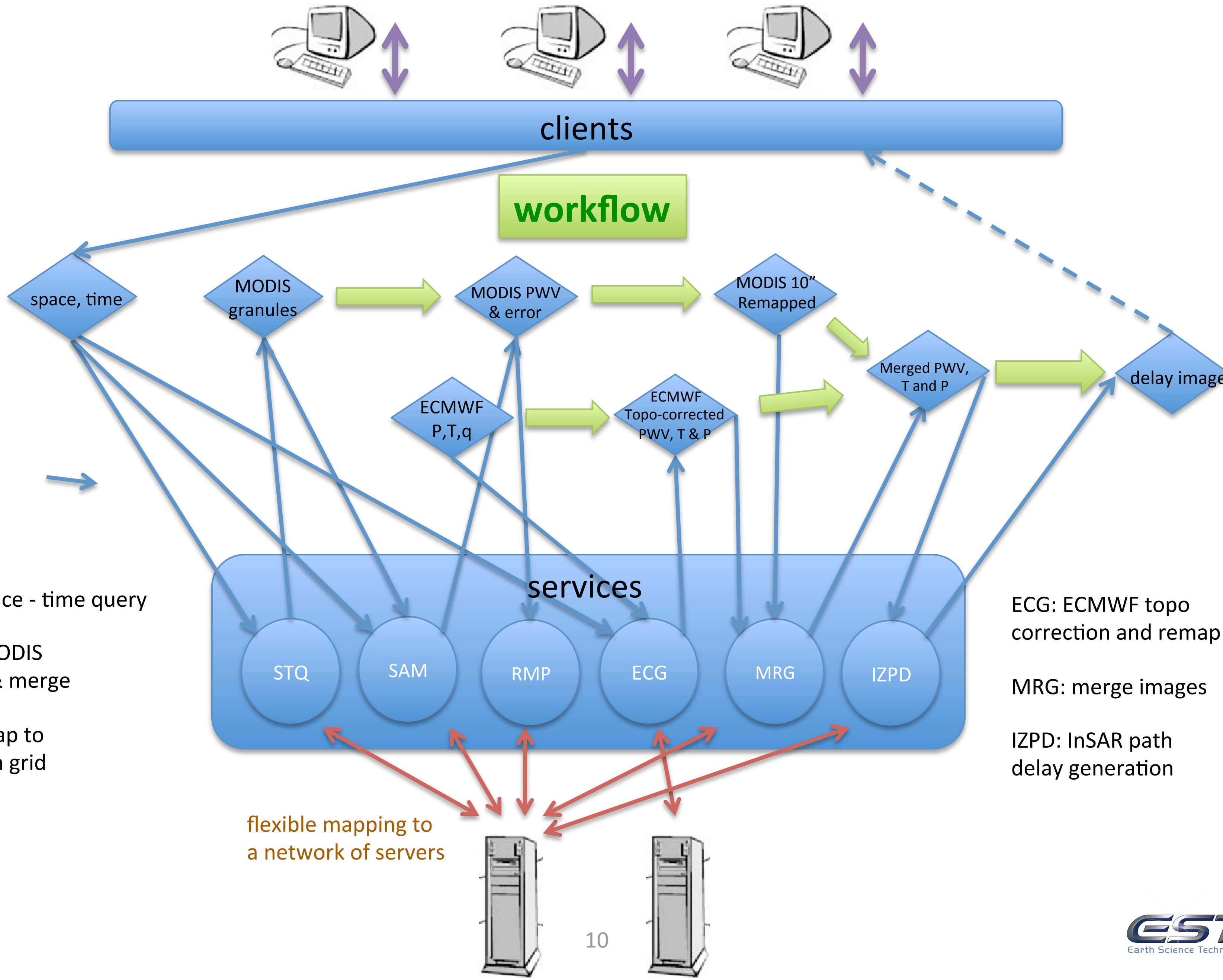
The layer thicknesses d_i^{SBL} are obtained by correcting the original thicknesses in the ECMWF model by using the correct topography

$$d_i^{SBL} = \frac{D_{total}^{BL,SRTM}}{D_{total}^{BL,ECMWF}} d_i^{ECMWF}$$

Using multiple data sets with height registered temperature and water vapor, delays from integrated products, such as the MODIS total precipitable water vapor, can be used in the general delay equation to provide more accurate delay estimates.

OSCAR IT Structure

Functional Architecture Diagram



STQ: space - time query

SAM: MODIS subset & merge

RMP: map to common grid

ECG: ECMWF topo correction and remap

MRG: merge images

IZPD: InSAR path delay generation

OSCAR Web Services (I)

All OSCAR services are ReSTful web services.

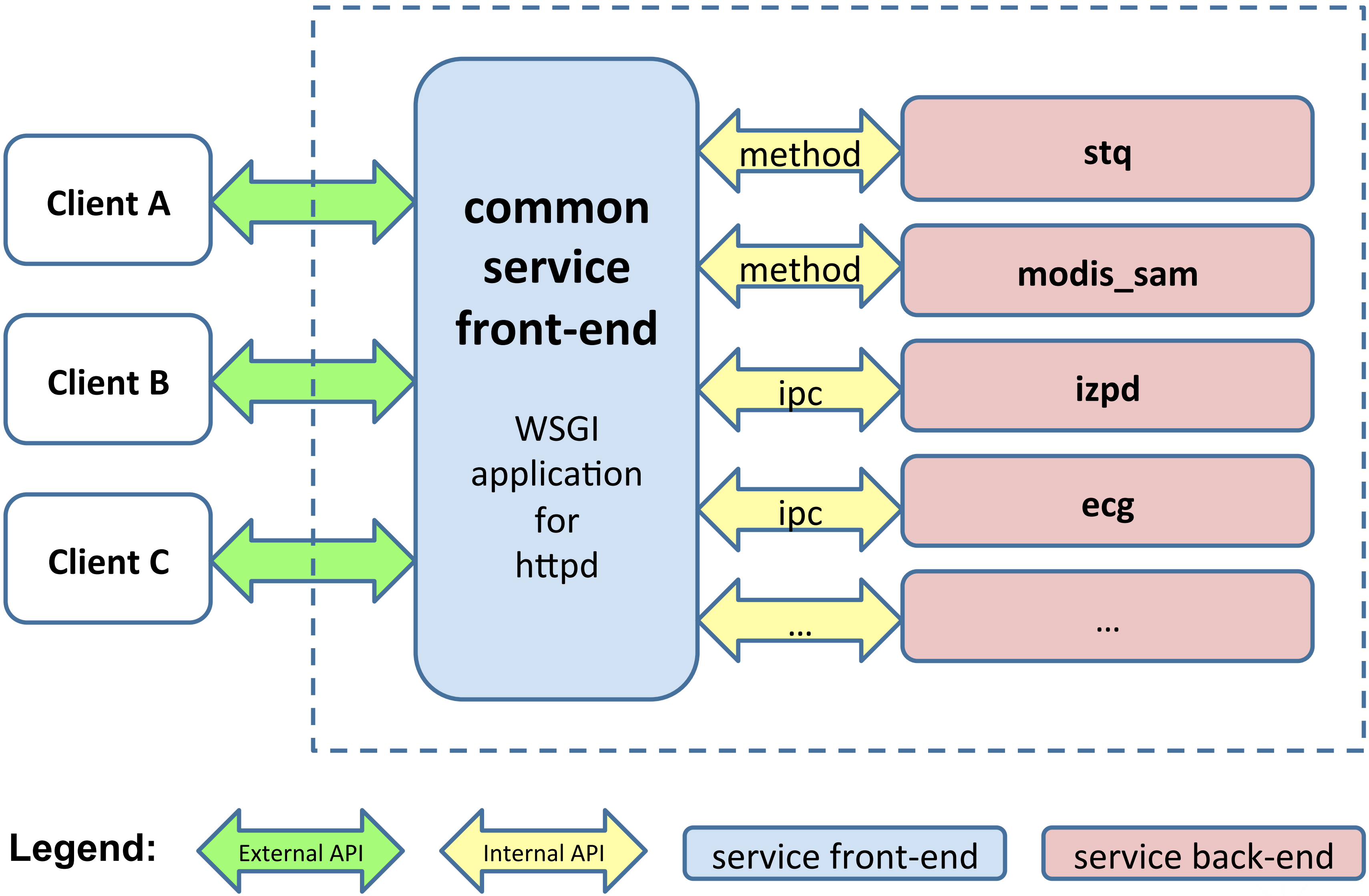
Each service consists of
- a service front-end, commonly shared among services, and
- an algorithmic back-end, which does data processing work.

The common service front-end is implemented as a python WSGI application for Apache httpd through mod_wsgi.

A service back-end can be
- a directly callable python module
- an external application, such as shell scripts.

The common service front-end knows how to invoke the back-end in both cases, as long as the back-end has clearly defined call methods or stdin, stdout and stderr streams suitable for inter-process communication (ipc).

OSCAR Web Services (II)



OSCAR Web Services (III)

Service Request

Each OSCAR service can be called by a client in either of the following 2 ways:

1. An HTTP GET using URL

```
http://hostname:port/service/name?queryString
```

2. An HTTP POST with `queryString` as message body using URL

```
http://hostname:port/service/name
```

in which `queryString` is a query expressed in JSON format and `name` is the short name of one of supported services, such as stq, modis_sam, izpd, ecg, etc.

If query is empty, service usage will be returned.

OSCAR Web Services (IV)

Service Response

The response of an OSCAR service is a JSON object, either

`{"query": queryObject, "result":resultObject}`

if successful, or

`{"error": errorObject}`

if failed with reportable error.

`queryObject` is a literal copy of query used, always a dictionary.

`resultObject` is a list or dictionary containing result or links to results.

`errorObject` is a dictionary containing full and/or abbreviated error message.

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MODIS Data Quality Screening Service (DQSS)

Metadata as Webified Virtual Data

Metadata: "data about data".

OSCAR project uses various metadata from different sources.
One example is a set of quality control (Q/C) parameters applied to MODIS level 2 water vapor measurements.

Virtual data: a leaf entity in a webification (w10n specification) tree, usually a data array, that does not physically exist, but is dynamically instantiated using a formula.

A MODIS DQSS has been created by implementing Q/C mask as a virtual data array. It is available for every MODIS granule file and can be accessed in the same way as real data arrays. Example:

http://oscar1/data/.../MOD05_L2.A2009182.1645.005.2009183041955.hdf

Benefits:

(1) uniform meta/data access
(2) algorithm and scheme transparency
(3) simplified data provenance and more

Correction Algorithm

Atmospheric Data Sets

- MODIS near-IR total precipitable water vapor
  - Quality control, error characterization, bias corrections and remapping
- ECMWF Global Analysis
  - Bias correction, remapping and topography correction
- **Goal: To combine data sets using Bayesian statistics**.
  - Requires error estimates, which must be inferred empirically

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MODIS water vapor correction model

Basic principles

- There is a scale uncertainty in MODIS near-IR water vapor products
- Only one continuous GPS station is required to calibrate MODIS scale uncertainty within a 2,030 km × 1,354 km MODIS scene
- GPS and MODIS data can be integrated to provide regional water vapor fields with a spatial resolution of 1 km × 1 km

References

Li, Z., J.-P. Muller, and P. Cross (2003), Comparison of precipitable water vapor derived from radiosonde, GPS, and Moderate-Resolution Imaging Spectroradiometer measurements, JGR, 108, 4651.

Li, Z., J.-P. Muller, P. Cross, and E.J. Fielding (2005), Interferometric synthetic aperture radar (InSAR) atmospheric correction: GPS, Moderate Resolution Imaging Spectroradiometer (MODIS), and InSAR integration, JGR, 110 (B3), B03410.

MODIS Quality Control Model

Basic principles

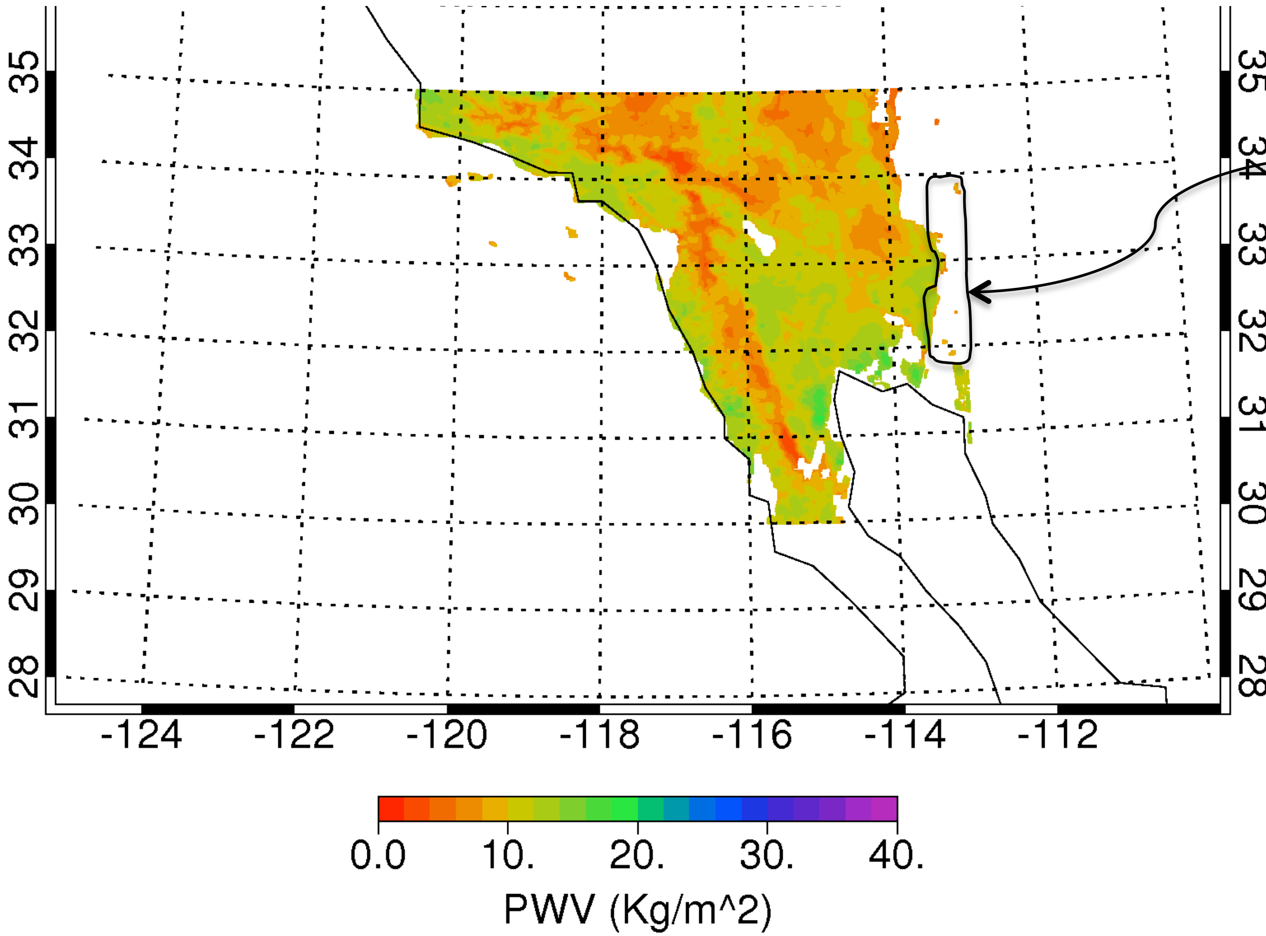
- Comparison of MODIS NIR water vapor with GPS, radiosondes and AERONET Sun photometer, clear pixels
  - RMS differences (σ) 5.44 kg/m^2 at 1 km spatial resolution
- Prasad, A.K. & Singh, R.P., 2009. Validation of MODIS Terra, AIRS, NCEP/DOE AMIP-II Reanalysis-2, and AERONET Sun photometer derived integrated precipitable water vapor using ground-based GPS receivers over India, *J. Geophys. Res.,* 114**,** D05107.
- Unusable over clouds
  - product is precise, but inaccurate because it misses column below the cloud
- Imprecise over water
  - Weak reflected signal, but not important for InSAR which is over land
- Unreported over heterogeneous surface, glint ....
  - indicated by fill value and *Quality_Assurance_Near_Infrared* parameter
- Quality degrades near low Q/A identified pixels, but not reported as low Q/A or cloudy.

MODIS Quality Control Parameters

- Algorithm to create a Q/C mask of when to use MODIS data, 1 –> data is useful
- Parameters in MODIS products
  - Water_Vapor_Near_Infrared (units 1cm = 10 kg/m^2)
    - Fill value -9999
    - Bad if set to fill
  - Cloud_Mask_QA
    - Cloud Mask Cloudiness Flag
      - Bits 2-3
      - Cloudy if < 2
  - Surface Type Flag
    - Bits 7-8
    - Water surface if < 2
  - Quality_Assurance_Near_Infrared
  - Total Precipitable Water (NIR) Usefulness Flag
    - Bit 1
    - Not useful if = 0
- MOD Q/C mask

$$\text{q/c mask} = \begin{cases} 0 & \text{if any condition is true} \\ 1 & \text{if all conditions are false} \end{cases}$$

Quality-controlled MODIS NIR Water Vapor

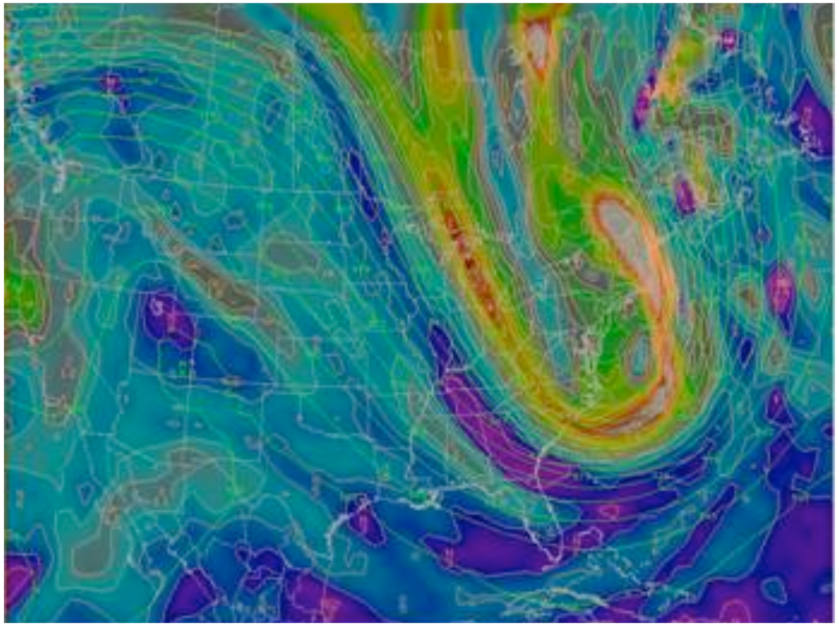


Low values adjacent to Q/C region are probably inaccurate although not flagged as such.

ECMWF Forecast/Analysis Data

- Global operational deterministic weather forecast model
  - ¼°, 90 vertical levels (17 levels in boundary layer)
  - Increasing to $^{1}/8$° in W 09, ½° prior to S06
  - assimilation of satellite, ground, radiosonde and ship and aircraft observation

500 hPa wave height
28 Oct 2008 – Extreme weather event

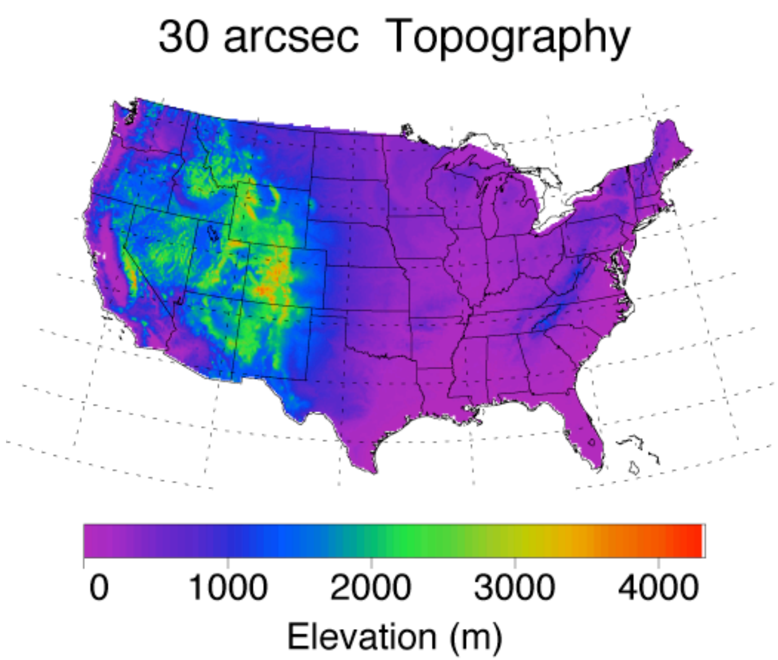


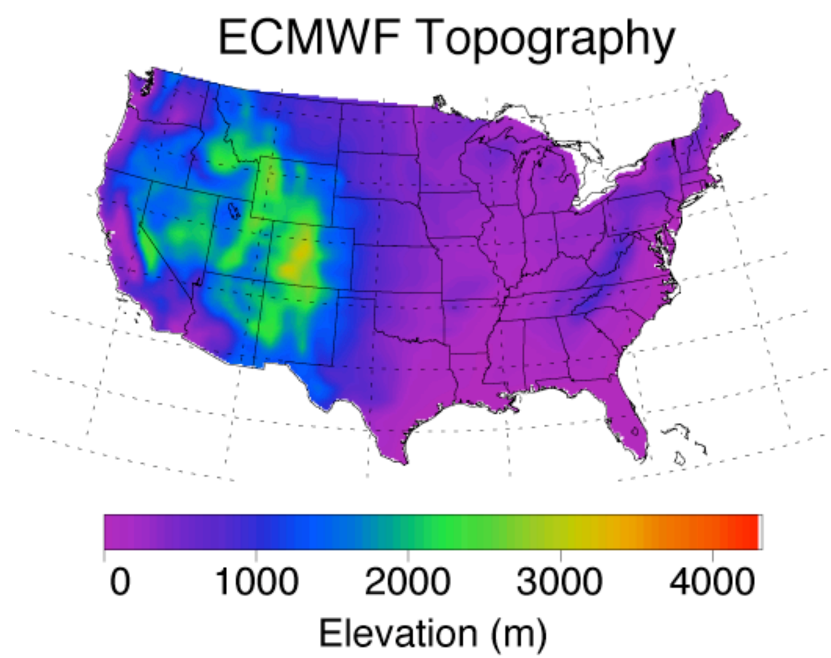
ECMWF Water Vapor Error Estimate

- ECMWF was validated with GPS and radiosonde data over Europe during Mesoscale Alpine Experiment, Special Observing Period (MAP-SOP) 1999.
  - Dry bias -1 kg/m^2 (-5.5%)
  - 2.6 km/m^2 (13%) RMS error
  - Bock, O., Keil, C., Richard, E., Flamant, C. & Bouin, M.N., 2005. Validation of precipitable water from ECMWF model analyses with GPS and radiosonde data during the MAP SOP, *Q J Roy Meteor Soc,* 131**,** 3013-3036.
- Spatial resolution 0.25°

ECMWF Topographic Corrections

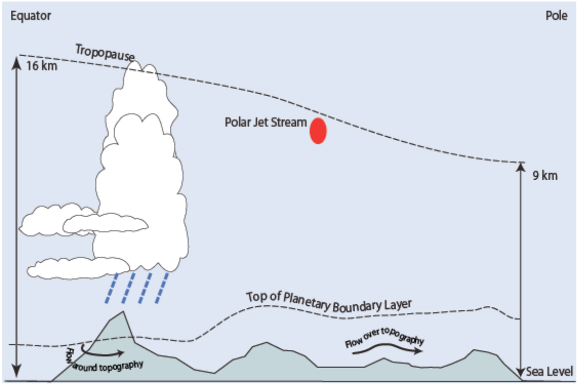
- Coarse spatial resolution of ECMWF topography introduces errors in local water vapor which can be corrected through a local topography correction.

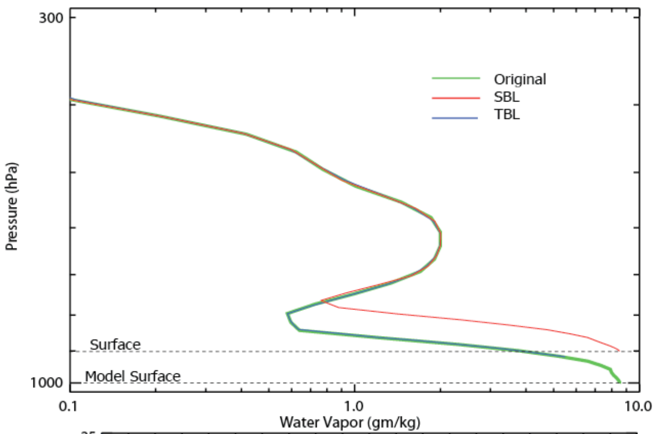


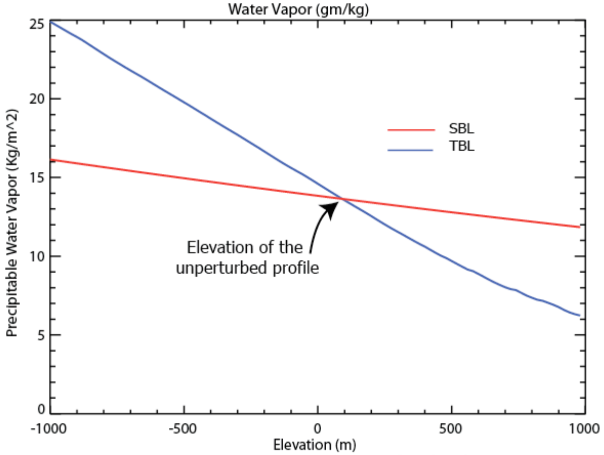


Numerical Weather Forecast Topography Correction Models

- Hypotheses on scales at which approximation is applied:
  - No local sources of water vapor
  - No adiabatic heating or cooling
- Stretched Boundary Layer Approximation
  - Surface water vapor mixing ratio and temperature along surface is conserved
  - Flow is along slope
  - Free troposphere structure unperturbed by topography
- Truncated Boundary Layer Approximation
  - Flow is around obstacles
  - Profile is cut-off by ascending slopes
  - Depressions fill with uniform surface water vapor mixing ratio air.





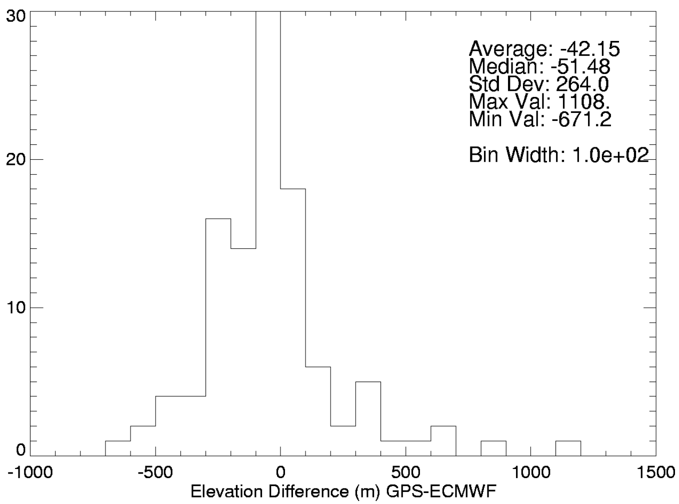


Analysis and Validation of Correction Algorithms

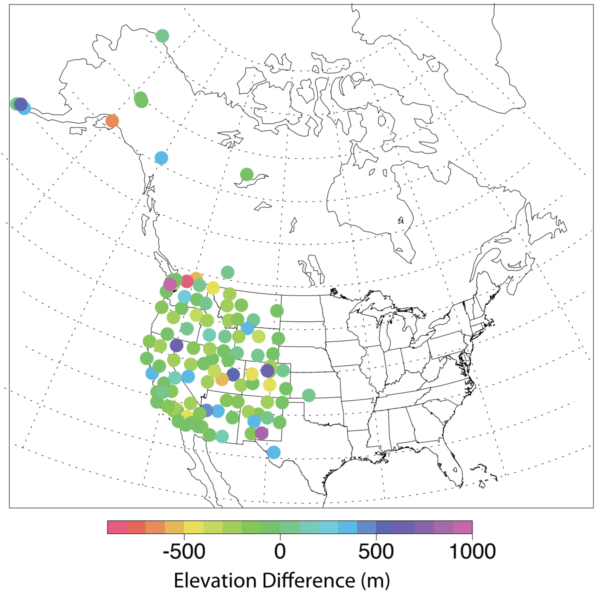
<u>Algorithm testing</u>

- Use GPS ground stations with meteorology packages
- Sort stations by model elevation error
- Compare surface pressure and total precipitable water vapor before and after stretched boundary layer correction

GPS-ECMF elevation difference



Location of GPS stations



Validation of Topography Correction Models

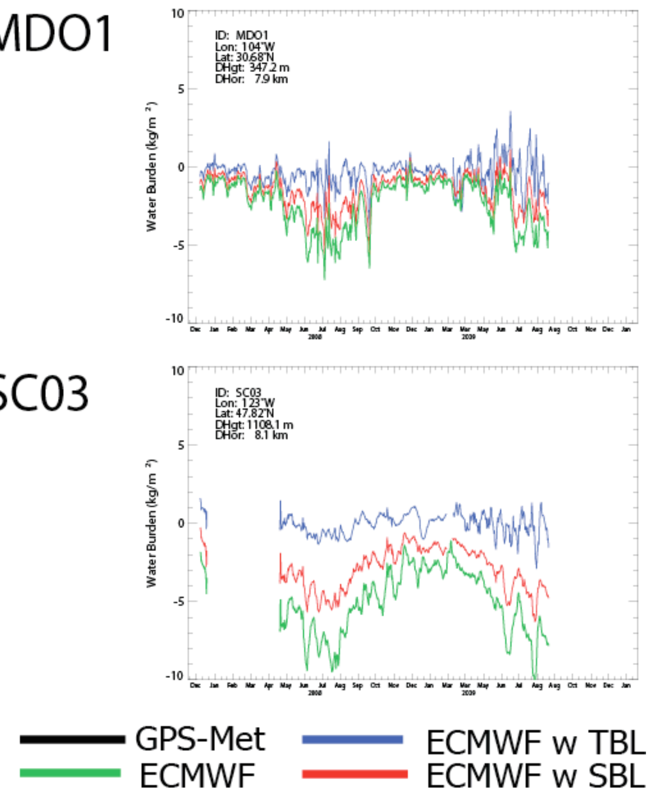
Time Series

- Comparison of GPS and corrected and uncorrected ECMWF water vapor
- Time series show strong seasonal component to error
  - 1-week moving window averaging applied
- SBL tends to under correct while TBL tends to over corrects

Water Burden Difference from GPS

MDO1

SC03



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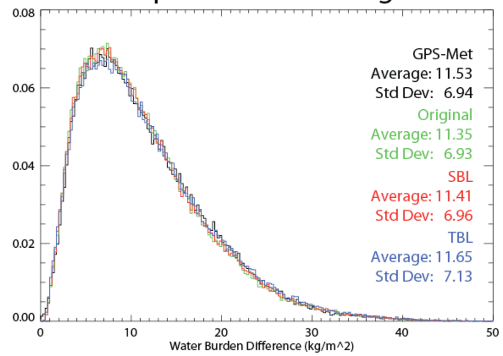
Validation of Topography Correction Models

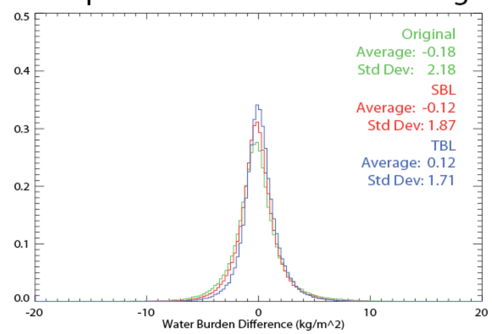
Histograms

- Variability of water vapor
  - mean of 11.5 kg/m^2
  - Standard dev. ~7 kg/m2.
- Variability after removing NWF
  - better than 2 kg/m^2.
  - dominated by error in the original NWF data.
- Uncorrelated with distance to grid point
  - Improved spatial resolution not important
- Probability conditional on elevation difference
  - (GPS-met - NWF).
  - TBL best for surface below model surface
  - SBL best for surface above model surface

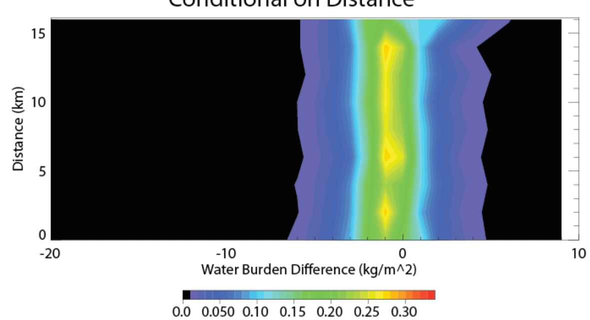
Water Vapor Burden Histograms



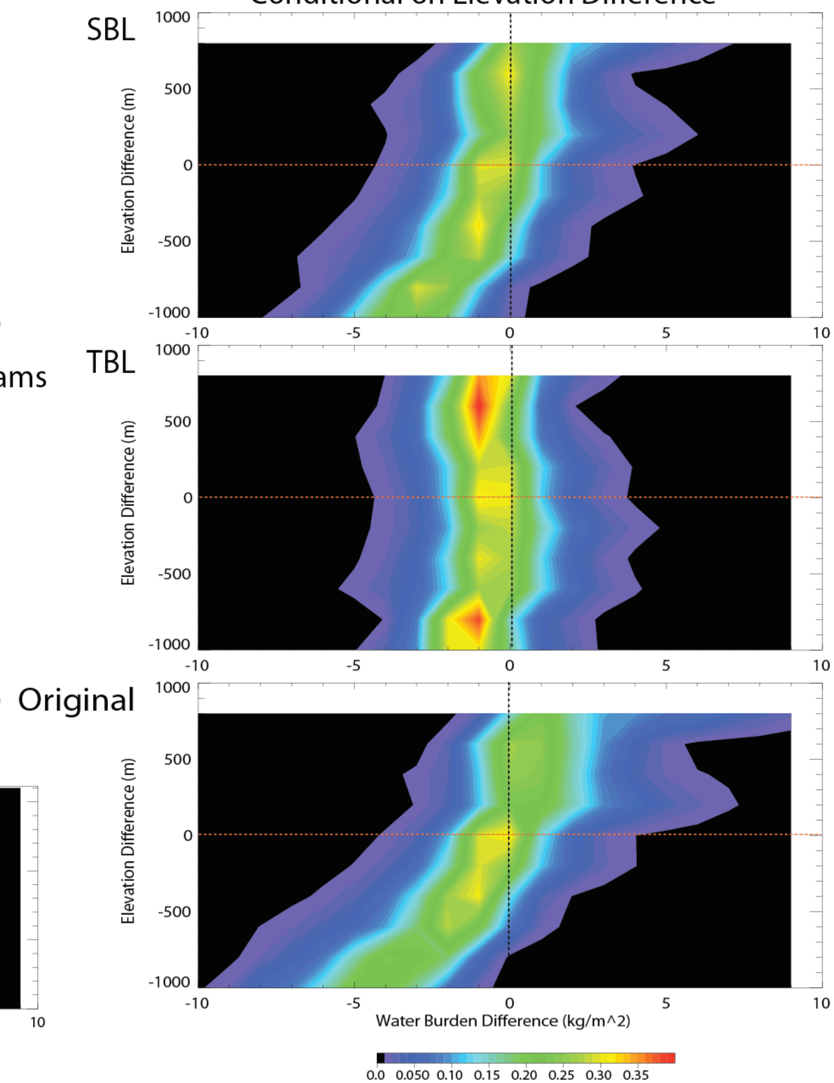
Water Vapor Burden Difference Histograms



Water Vapor Burden Difference Histogram Conditional on Distance



Water Vapor Burden Histrograms Conditional on Elevation Difference



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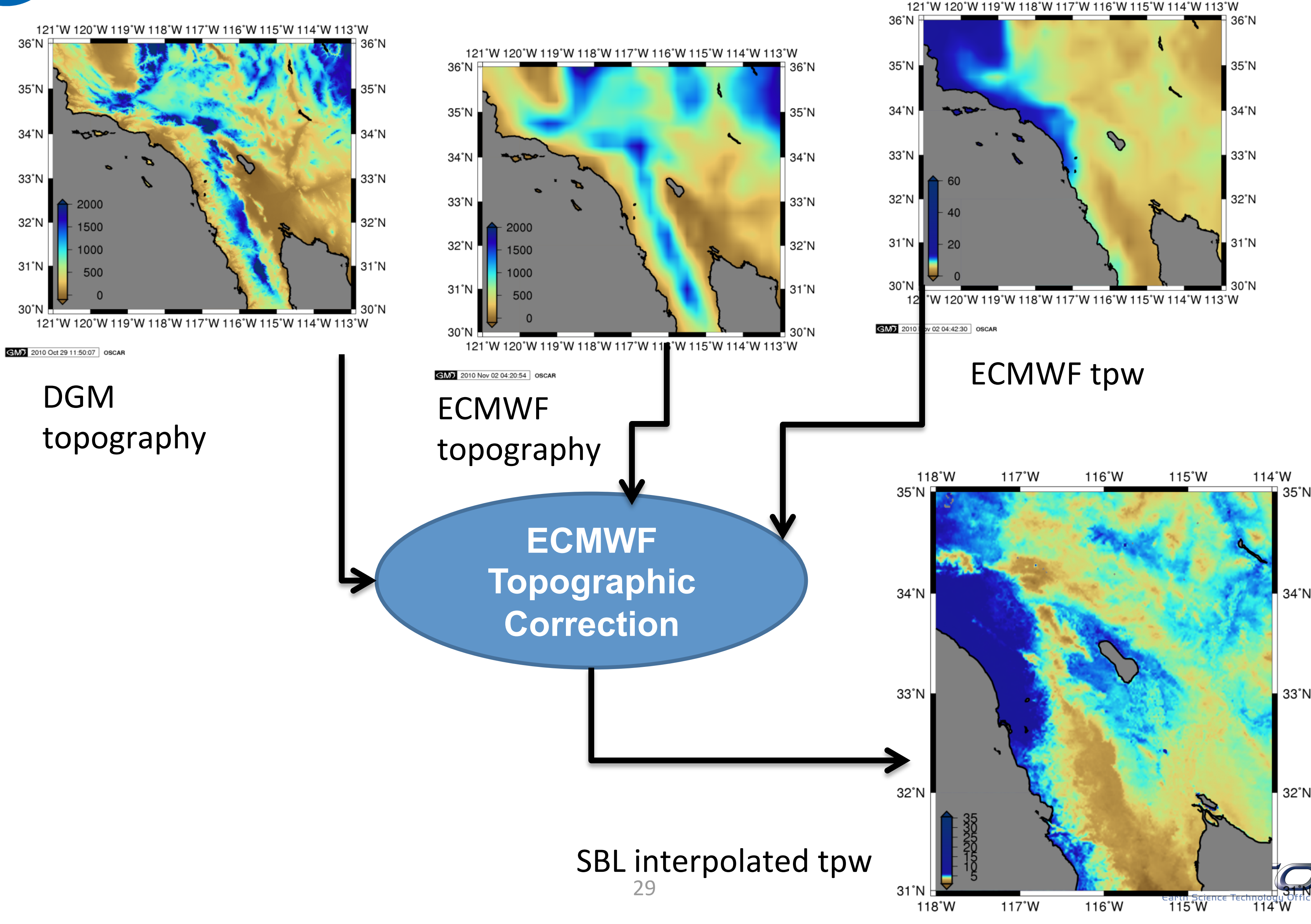
Data Flow

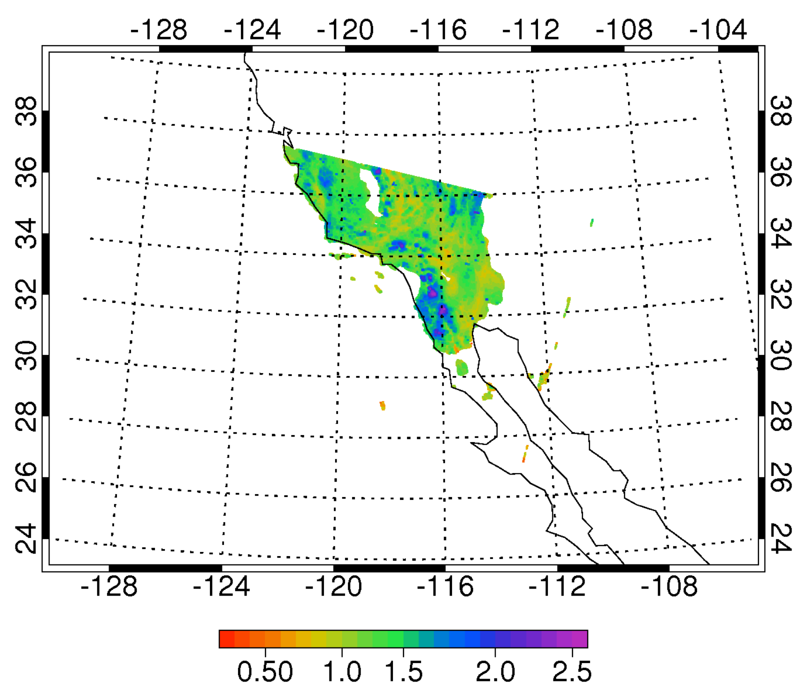

DGM topography
ECMWF topography
ECMWF tpw
ECMWF Topographic Correction
SBL interpolated tpw

ECMWF Bias Correction Models

- ECMWF validation shows a 5.5% dry bias
- Topographic correction validation studies shows regional and seasonal bias between ECMWF and MODIS water vapor
- Water vapor is modulated by topography
  - A fixed bias correction produces negative total water vapor at high elevation.
- Appropriate bias correction should be a scaling factor
  - Dynamic
  - Derived from coincident, collocated data

ECMWF Bias Correction Algorithm

- Remap topographically corrected ECMWF and MODIS data to a common grid.
- Ratio median ECMWF to median MODIS water vapor in 2° lon-lat bins to produce scaling correction *f*
  - MODIS Q/C mask is 1
- Apply annealing algorithm to extend *f* to empty bins
  - Iteratively extend *f* into empty bins using median of *f* in eight surrounding bins
- Bilinear interpolate *f* to 0.005° regular grid



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Merging Algorithm

- Bayesian algorithm, average of MODIS and ECMWF water vapor weighted by square errors
- Bias-corrected, topographically corrected ECMWF water vapor has constant error.
- MODIS error is 2x ECMWF error, but
  - spatial resolution of MODIS is 25x higher
  - At same spatial resolution, MODIS error is 12.5x smaller
- Smooth MODIS qc_mask to same resolution as ECMWF
  - Grid MODIS qc_mask to 0.005° grid
  - Run a 50x50 (0.25° wide) box car smoothing to gridded qc_mask
- Use the following error model error model

$$\frac{\sigma^2_{\text{ECMWF}}}{\sigma^2_{\text{MODIS}}} = \frac{\text{smoothed\_qc\_mask}}{1 - \text{smoothed\_qc\_mask}}$$

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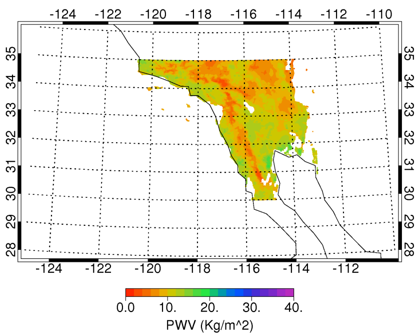
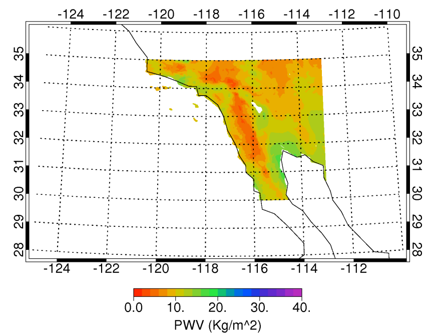
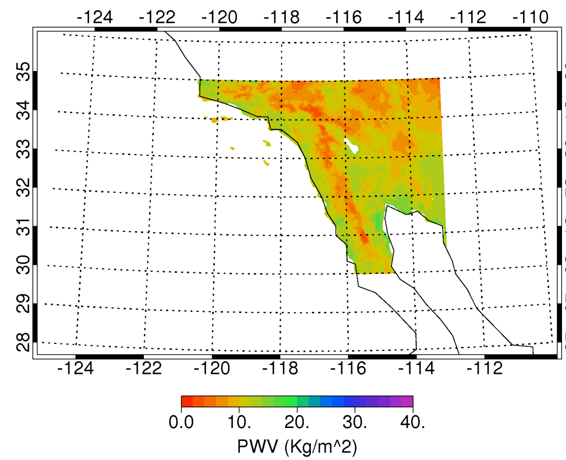
Example Baja California 16 Apr 2010



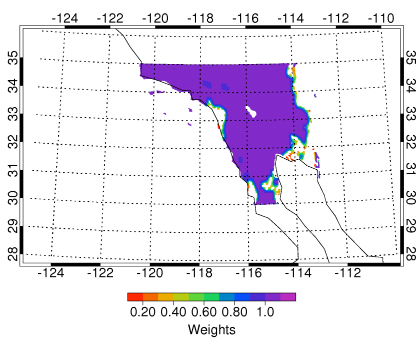
Q/C'd MODIS



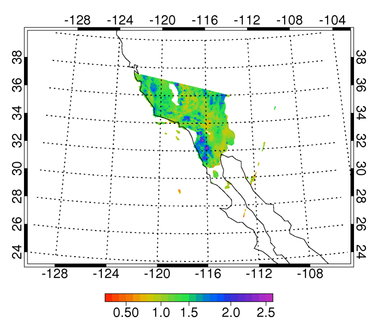
ECMWF



Merged



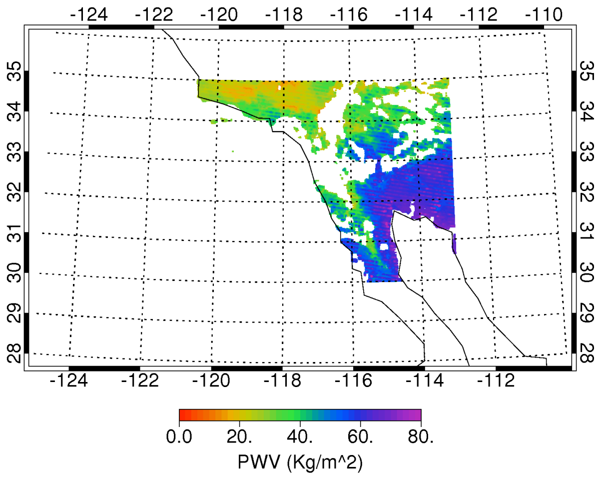
MODIS Wgt



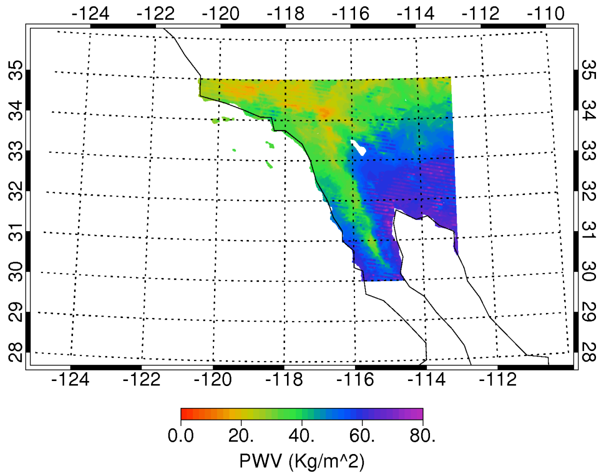
Bias Factor

Example Baja California 29 Aug 2008

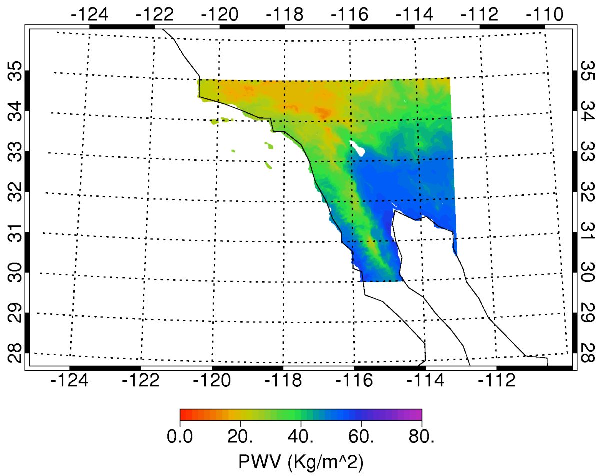
Q/C'd MODIS



Merged



ECMWF



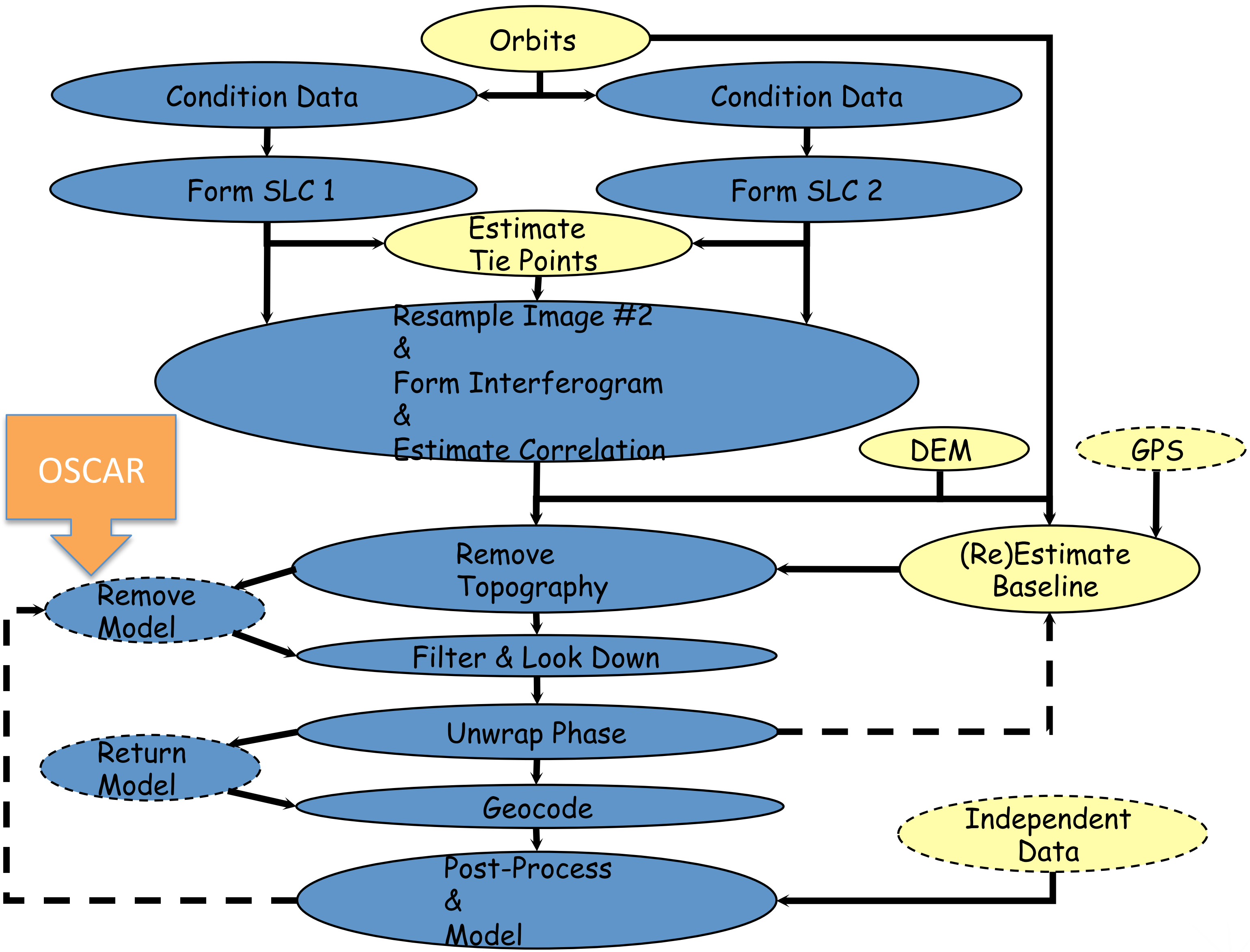
- Q/C MODIS shows striping
- 60 kg/m^2 corresponds to 36 cm of InSAR path delay.

Applications

ROI_pac and ISCE InSAR packages

- ROI_pac InSAR package (see http://roipac.org) was written at JPL and Caltech over the last 15 years
- It is a full end-to-end InSAR package going from raw data to fully processed and geocoded interferograms
- Atmospheric correction models can be inserted into the processing workflow as gridded latitude-longitude maps of path delay
- Next-generation replacement for ROI_pac is ISCE, the InSAR Scientific Computing Environment, under development under AIST

ROI_pac flow chart



courtesy Mark Simons

Support of DESDynI Mission Definition Study Group

- Atmospheric effects are largest source of error in InSAR measurements
- MDSG is using OSCAR server to collect MODIS water vapor data for each 1x1 degree cell of land area
- Then the spatial statistics of the water vapor delay are calculated
- Spatial statistics are then included in error model calculations

OSCAR and UAVSAR

- UAVSAR is a NASA airborne interferometric synthetic aperture radar (InSAR) system built and operated by JPL
- At present, UAVSAR is flown on NASA Gulfstream III at 41,000 ft (12.4 km)
- UAVSAR measurements include nearly all of tropospheric water vapor delay
- Studying possible infusion of OSCAR corrections into standard UAVSAR processing chain

Conclusion

- Developed a web service system to compute radar propagation delays in troposphere using remote sensing and weather forecast model (http://oscar.jpl.nasa.gov)
- OSCAR web service APIs are lightweight and easy to use. Clients are available in AJAX for standard web browser, Python and MATLAB
- OSCAR was demonstrated using merged MODIS and ECMWF water vapor data
- OSCAR applications include inter-operability with InSAR data processing s/w ROI_pac, support of DESDynI mission definition study group and UAVSAR image corrections